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Research and Development Advances Impacting Diminishing Manufacturing Sources and Material Shortages Management

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About This Publication

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Executive Summary

The 2016 SD-22, *Diminishing Manufacturing Sources and Material Shortages (DMSMS): A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program*, defines DMSMS management as a multidisciplinary process to identify issues resulting from obsolescence, loss of manufacturing sources, or material shortages; to assess the potential for negative impacts on schedule and/or readiness; to analyze potential mitigation strategies; and then to implement the most cost-effective strategy.

This document identifies research and development (R&D) advances (including scientific developments, new materials, and manufacturing and management technologies) that might have the potential to improve some aspects of DMSMS management. This document does not examine these R&D advances exhaustively or in detail. It provides a brief description of the advances, summarizes their potential impact, highlights some organizations pursuing work in these areas, and points out prospective DMSMS applications. It is designed to be an initial step in increasing awareness and categorizing some of the more important R&D advances that may affect DMSMS management. More detailed investigations are necessary to understand the advances and evaluate their utility.

The principal data source for this research was not-for-attribution interviews with approximately 30 subject matter experts (SMEs). SMEs were asked what developments that they saw now and in the near future had the potential to impact Department of Defense (DOD) obsolescence issues. A total of 25 R&D developments with impacts on DMSMS were identified and organized around the potential impact on DMSMS capability, as follows:

- R&D advances enabling repairs not possible or cost prohibitive in the past, and longer-lasting replacement items
- Advances improving the cost effectiveness of reverse engineering and redesign of materials and structural, mechanical, and electrical items
- Advances improving the cost effectiveness of reverse engineering and redesign of integrated circuits
- New approaches to dealing with software obsolescence and vulnerabilities
- New technologies and methods to assist the internal manufacturing of DOD replacement parts
- R&D advances enabling better DMSMS management

While all of these technological advances will help DOD better address obsolescence and other DMSMS problems, there are two major barriers to their exploitation by the DMSMS community—knowledge of these current R&D activities and a mechanism to disseminate that knowledge. The DMSMS community might even consider making investments to acquire and develop expertise in some of these new technologies.

Some technology changes may exacerbate DOD's DMSMS problems. Some SMEs indicated that the pace of technology change, commercial application domination, and rapid commercial abandonment of parts in favor of new technologies suggest that DOD will have an increasingly more difficult, costly effort to deal with obsolescence, despite exploiting technological changes that can help mitigate impacts. In addition, many new technological changes may lead to other, sometimes unanticipated changes that can cause difficulties and disruptions.

The following recommendations should be considered in developing plans to address the opportunities and threats of technological advances.

Establish a DMSMS Technology Watch Capability

A key DMSMS technology management issue is, "When should government fundamentally support a new technology/product that may be very useful for DMSMS mitigation but lacks sufficient commercial demand?" There are many existing or potential R&D developments that hold great promise for DMSMS, but they may not be explored by commercial industry because of its preference for short-life, use-and-discard products. DMSMS decision makers need to understand likely commercial support and development to judge whether a promising new technology will get developed and implemented without DOD support. Such support should also consider the need for improved data integration and IT systems that enable these advances. A DMSMS watch capability could be used to identify and make recommendations concerning such situations.

Expand the Annual DMSMS Conference Role in Communicating R&D Information and Promoting Helpful R&D Advances

A significant portion of the annual DMSMS conference could be devoted to this subject. Conference tracks could be designed to provide information on the latest developments and risk areas and potentially the need for greater investment. As part of this effort, conference planners may want to consider significant outreach beyond defense industries to include more corporate commercial interest to expand the size and scope of technological issues considered. They will accomplish such outreach by emphasizing obsolescence management and problem mitigation to expose the DMSMS community to more information on promising R&D advances and new industry contacts. Ideally, these efforts to disseminate information on R&D advances would include establishing communities of interest and other user-focused experience-sharing mechanisms.

Do Not Allow R&D Advances to Be Used as an Excuse Not to Apply Best DMSMS Management Practices

R&D advances in techniques for resolving DMSMS issues hold great promise for mitigating the effects of DMSMS issues. These advances, however, are not a substitute for applying the best DMSMS management practices promulgated in the SD-22. This is especially true for additive manufacturing (AM) where DOD must be careful not to overly rely on AM for sparing and

consequently cut back on spares production and stockpiles. This will lead to more DMSMS issues and more opportunities for counterfeits and malicious insertions. For example, it is important to

- design in a way that reduces future DMSMS issues,
- ensure that development and sustainment contracts have effective DMSMS requirements,
- ensure that complete item and system data are owned or readily obtainable,
- conduct life-of-need buys when opportunities present themselves, and
- anticipate and proactively prepare for new counterfeiting threats.

Contents

1. Introduction

Diminishing Manufacturing Sources and Material Shortages (DMSMS) management is a "multidisciplinary process to identify issues resulting from obsolescence, loss of manufacturing sources, or material shortages; to assess the potential for negative impacts on schedule and/or readiness; to analyze potential mitigation strategies; and then to implement the most cost-effective strategy."[1]

This document identifies research and development (R&D) advances (including scientific developments, new materials, and manufacturing and management technologies) that might have the potential to improve some aspects of DMSMS management. This document does not examine these R&D advances exhaustively or in detail. It provides a brief description of the advances, summarizes their potential impact, highlights some organizations pursuing work in these areas, and points out prospective DMSMS applications. It is designed to be an initial step in increasing awareness and categorizing some of the more important R&D advances that may affect DMSMS management. More detailed investigations are necessary to understand the advances and evaluate their utility. R&D advances impact DMSMS issues in three major areas:

- Implementation of resolutions that produce replacements for electronic items
  - These resolutions are often associated with low-volume production because the Department of Defense (DOD) continues to use and demand older electronic items associated with systems that are operated for decades. Electronic item production is primarily driven by rapidly advancing new technologies, with the dominant consumer market quickly abandoning old chips and systems.
- Implementation of resolutions that produce replacements for materials and structural, mechanical, and electrical (MaSME) items
  - These resolutions are often associated with original producers who (1) are no longer in business or (2) refuse to or cannot (because manufacturing details have been lost) make low-volume runs of very old items. For MaSME item obsolescence, some new technologies are enabling both repairs that could not be made in the past and some better ways to remake a part than the original.
- Improvements to the DMSMS management processes themselves
  - These improvements may be associated with new databases and information technology advances that can help DOD address obsolescence problems better.

Some R&D advances may increase DMSMS challenges. For example, integrated circuits are being abandoned by manufacturers faster and additive manufacturing (AM) may increase the scope of counterfeit problems. Therefore this document also assesses new means of managing

[1] SD-22, *Diminishing Manufacturing Sources and Material Shortages* (*DMSMS*)*: A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program,* January 2016.

obsolescence and DMSMS problems that are not going to be radically reduced by better technologies in the foreseeable future.

Not-for-attribution interviews with approximately 30 subject matter experts (SMEs) were the principal data source for this research. SMEs were asked what developments that they saw now and in the near future had the potential to impact DOD obsolescence issues. A total of 25 R&D developments with impacts on DMSMS were identified, as shown in Table 1.

Table 1. R&D Advances with DMSMS Potential

Electronic:	Materials, Structural, Mechanical, and Electrical Items:
1. Electronic Reverse Engineering Advances	1. Additive Repair Advances
2. Rapid Circuit Redesign Advances	2. Intermetallic Alloy Advances
3. Emulation Technology Advances	3. Ceramic Matrix Composites Advances
4. Field Programmable Gate Array Advances	4. New Carbon Fibers and Carbon Fiber Nanotubes Advances
5. Assembled Replacement Integrated Circuit Advances	5. Mechanical Reverse Engineering Advances
6. Interposer Advances	6. Integrated Computational Materials Engineering Advances
7. Analog/Linear Microcircuit Emulation Production Advances	7. Qualification and Testing Advances
8. Die Extraction/Reassembly Advances	8. Additive Manufacturing Advances
9. Multibeam Technology Advances	9. High-Speed Machining Advances
10. Direct Write Laser Technology Advances	
Software	
1. Software Obsolescence Prevention Advances	
DMSMS Management:	
1. DMSMS Cost Estimation Advances	
2. Designing for DMSMS Advances	
3. Data Capture and Integration Advances	
4. Digital Thread Advances	
5. Database, Collaboration Tool, and Information Management Advances	

In addition to breaking out R&D advances by electronics, mechanical, and management, this document groups these advances based on their potential impact on DMSMS capability:

1. Enabling repairs not possible or cost prohibitive in the past, and longer-lasting replacement items
2. Improving the cost effectiveness of reverse engineering and redesign of MaSME items
3. Improving the cost effectiveness of reverse engineering and redesign of integrated circuits
4. Dealing with software obsolescence and vulnerabilities
5. Assisting the organic manufacturing of DOD replacement parts
6. Enabling better DMSMS management.

Table 2 shows these 25 new technologies broken into the six DMSMS application areas.

Table 2. R&D Advances by DMSMS Application Area
1. Enabling repairs not possible or cost prohibitive in the past, and longer-lasting replacement parts
Additive Repair Advances
Intermetallic Alloy Advances
Ceramic Matrix Composites Advances
New Carbon Fibers and Carbon Fiber Nanotubes Advances
2. Improving the cost effectiveness of reverse engineering and redesigns of MaSME items
Mechanical Reverse Engineering Advances
Integrated Computational Materials Engineering Advances
Qualification and Testing Advances
3. Improving the cost effectiveness of reverse engineering and redesign of integrated circuits
Electronic Reverse Engineering Advances
Rapid Circuit Redesign Advances
Emulation Technology Advances
Field Programmable Gate Array Advances
Assembled Replacement Integrated Circuits Advances
Interposer Advances
4. New approaches to dealing with software obsolescence and vulnerabilities
Software Obsolescence Prevention Advances
5. Assisting the organic manufacturing of DOD replacement parts
Additive Manufacturing Advances
High Speed Machining Advances
Analog/Linear Microcircuit Emulation Production Advances
Die Extraction/Reassembly Advances
Multibeam Technology Advances
Direct Write Laser Technology Advances
6. Enabling better DMSMS management
DMSMS Cost Estimation Advances
Designing for DMSMS Advances
Data Capture and Integration Advances
Digital Thread Advances
Database, Collaboration Tool, and Information Management Advances

Each of these six DMSMS impact areas are addressed in turn in this document, followed by conclusions and recommendations.

2. R&D Advances Enabling Repairs Not Possible or Cost Prohibitive in the Past, and Longer-Lasting Replacement Parts

A. Additive Repair Advances

Description of Advances

New technologies and processes are allowing repairs of parts that previously would have been discarded, requiring a complete replacement. Laser cladding/welding/sintering deposits material by using a laser to melt powdered or wire feedstock material to fabricate or coat a part. Plasma deposition results from high-power laser pulses in a vacuum chamber that melt, evaporate, and ionize material from the surface of a target, producing a transient, highly luminous plasma plume while depositing material on the target surface. Kinetic cold spray is an additive manufacturing process for depositing metals, ceramics, or plastics onto surfaces by kinetic energy (particles accelerated to supersonic speeds) rather than thermal energy

Potential Impact

Advances in additive R&D, such as cold spray deposition with lasers, are enabling repairs that were not possible or were cost prohibitive in the past. The costs associated with the application of these new technologies have been around 10–15 percent of costs to manufacture new components. The improved wear and corrosion protection from the coatings can yield a part with a longer lifespan than the original.[2]

Of these types of technologies that can enable repair additively, laser cladding has been used for the past 17 years. Plasma deposition is fairly new. Kinetic cold spray will become operational in FY16.

Organizations Funding/Working on the Advances

The Navy has been a leader in additive repair technologies. It has exploited and developed several new processes that allow the repair of parts that would have been discarded and replaced previously. The Naval Undersea Warfare Center (NUWC), Keyport, uses advanced laser cladding/welding for dimensional restoration of parts.[3] The Navy has also been developing technologies that use plasma deposition and kinetic cold spray.

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[2] SME interview, November 2015.

[3] NUWC Keyport, "Custom Engineered Solutions Program," March 26, 2015.

DMSMS Application

Several of these new technologies for additive repair have been successfully applied to obsolescence and DMSMS problems. These additive repair technologies restore damaged and corroded parts to their original condition, without the need for replacement parts.[4]

B. Intermetallic Alloy Advances

Description of Advances

Intermetallic alloys or what the Japanese refer to as “fine” ceramics are alloys with properties between ceramics and metals. These new alloys have improved, higher-temperature properties like ceramics, but metal alloy strength.

Potential Impact

New intermetallic alloys such as titanium aluminum are expected to offer expanded and improved repair opportunities for DOD.[5] The performance of metal alloys is highly dependent on relatively small differences in the arrangement of atoms. A few percent change in composition or slight modification in manufacturing processes improves qualities such as strength by 50 percent or more.[6] Given their metal alloy strength, these new intermetallic alloys provide more options in replacing parts with more capable and longer-lasting ones.

Organizations Funding/Using Technologies

The interviews conducted for this effort did not identify any DOD organizations using or funding research on intermetallic alloys.

DMSMS Application

While these new alloys are primarily seen as an application for new, original production, their longer lifespan has good DMSMS implications, reducing the need for replacements. But improvements offered by more advanced materials can sometimes create DMSMS management difficulties if the complex material is too difficult to repair.

C. Ceramic Matrix Composite Advances

Description of Advances

Ceramic matrix composites (CMCs) are an advanced category of materials that will likely play a major role in both new DOD systems and replacement parts. Conventional technical ceramics like alumina and silicon carbide fracture easily under mechanical or thermo-mechanical

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[4] SME interview, October 2015.

[5] SME interview, November 2015.

[6] National Institute of Standards and Technology, Material Genome Initiative website, https://mgi.nist.gov.

stress due to cracks initiated by small defects or scratches. To increase the crack resistance or fracture toughness, particles or fibers are embedded into the matrix.

Potential Impact

While more capable ceramic matrix composites are primarily applicable to new production, there will be opportunities to aid in sustainment by replacing less capable materials with these longer-lasting, stronger products.[7]

Organizations Funding/Working on the Advances

General Electric (GE) has been a leader in CMC development for jet engines, as CMCs are "as strong as metal, yet are much lighter and can withstand much higher temperatures." CMCs can operate at temperatures exceeding the capability of current nickel alloys typically used in high-pressure turbine jet engines. Because metal parts require extensive dedicated cooling air, which detracts from the primary engine airflow and reduces efficiency, and CMCs can operate with little or no cooling, this can provide a significant efficiency boost to jet engine performance.[8]

DMSMS Application

CMCs may be used as patch material for applications such as Space Shuttle repair in space (inspired by the Columbia disaster), surviving huge temperature swings, from minus 250 degrees Fahrenheit in orbit to 3,000 degrees during descent. Other applications include steering components for ballistic missile defense systems and rocket motor thrusters.

D. New Carbon Fiber and Carbon Fiber Nanotube Advances

Description of Advances

High-performance polyacrylonitrile-based carbon fibers (CFs) are highly engineered, unique, and proprietary in their manufacture and downstream applications. Individual carbon fiber producer companies (often one plant and even one specific production line) produce unique precursor fibers that are further processed into finished fibers through a specialized heating process specific to individual fiber producers and specific CF products. Finished fibers are used within specific downstream composite materials' supply chains that can often be unique to specific end-use applications, including highly engineered and complex systems such as aircraft, satellites, and missiles.

There are constant advances in CF materials and manufacturing technology that yield better, faster, and cheaper CFs, related intermediate materials, and finished composite structures. An

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[7] SME interview, November 2015.

[8] General Electric, "Ceramic Matrix Composites Improve Engine Efficiency," article on GE Global Research web page, downloaded February 2016, http://www.geglobalresearch.com/innovation/ceramic-matrix-composites-improve-engine-efficiency.

especially promising new technology is “carbon nanotubes,” which offer unique thermal and mechanical property improvements.[9]

Potential Impact

CFs offer unmatched strength and light weight advantages, vital for many DOD systems, especially in space and aerospace systems. However, the costs are high and the testing, qualification, and certification of fibers and their downstream composites are technically demanding and very time consuming. High reliability and consistency are often critical to high-consequence applications such as unmanned intelligence, surveillance, and reconnaissance aircraft and inter-continental ballistic missile rocket motor cases.

Organizations Funding/Working on the Advances

Funding and advances are being accomplished by the CF manufacturing firms.

DMSMS Application

Unlike additive manufacturing proponents, CF companies are not promoting CFs as a means of addressing obsolescence issues, but they do in theory offer DMSMS opportunities—especially where high strength to weight performance is desired and cost is less of a constraint.

CF SMEs interviewed were not aware of any example of a non-CF part being replaced by a CF part due to obsolescence problems. It could be feasible, but likely more expensive than the original, non-CF part. But this may be a feasible and desirable option in the future as CF performance continues to improve and costs fall.[10]

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[9] SME interview, November 2015.

[10] SME interview, November 2015.

3. Advances Improving the Cost Effectiveness of Reverse Engineering and Redesign of MaSME Parts

A. Mechanical Reverse Engineering Advances

Description of Advances

Digital tomography produces a three-dimensional image of the internal structures of a solid object by recording differences in effects of waves of energy passing through the structures. Scanning and tolerancing tools enable the generation of three-dimensional (3D) models of parts that can then be used as inputs to computer-aided design (CAD) models. Several new scanning and tolerancing tools were presented in August 2015 at a Joint Technology Exchange Group (JTEG) workshop, including software technologies such as Rapidform (reverse engineering); measuring technologies such as 3D laser tracker/scanners, offered by Leica and API, which use laser light for very accurate dimensional measurements; and 3D scanners.[11]

Potential Impact

Digital tomography has been used for years, but advances continue. With these advances, more surface detail is possible. Newer software and scanning and tolerancing tools quickly and more accurately create 3D geometric models of parts as input to CAD models.

Reverse-engineered original equipment manufacturer (OEM) parts libraries provide a less expensive alternative than the OEM or another company. Parts can be ordered on demand with lead times reportedly as short as two days and quantities as few as a single part.[12] A prototype of the part can be sent for approval of form and function.

Organizations Funding/Working on the Advances

The military services fund most of their reverse engineering R&D work, but some reverse engineering progress has been enabled with Defense Advanced Research Projects Agency (DARPA) funding.[13]

DMSMS Application

While they may not get as much attention as a breakthrough new technology that could facilitate a particular resolution, constant advancements in technologies that enable improvements in reverse engineering are also a key enabler of DMSMS resolutions. DMSMS organizations have

[11] JTEG meeting, August 25, 2015; Edward Ayer, AFSC/EN, "AFSC Reverse Engineering Overview," PowerPoint briefing presented at meeting.

[12] RapidMade website, http://www.rapidmade.com/reverse-engineering-and-3d-scanning.

[13] SME interview, November 2015.

used digital tomography for some time to enable reverse engineering. Continued advances in reverse engineering technologies are particularly important for DOD DMSMS on the mechanical side. When detailed production data on obsolete parts are not available (a frequent problem), DOD engineers must create the necessary documentation to produce or order equivalent parts. For example, using additive manufacturing to produce a replacement part for one that is no longer produced is not possible without detailed product specifications and production details; mechanical reverse engineering is often required to obtain this detail.[14]

B. Integrated Computational Materials Engineering Advances

Description of Advances

Integrated computational materials engineering (ICME) is the "integration of materials information, captured in computational tools, with engineering product performance, analysis, and manufacturing-process simulation."[15]

Potential Impact

ICME was identified about a decade ago because of the "significant potential for reducing component design and process development costs and cycle times, lowering manufacturing costs, improving the prognosis for material and component life, and, ultimately, allowing for agile response to changing market demands."[16] A National Institute of Standards and Technology (NIST) study explained that, in contrast to an empirical trial-and-error-based approach that may take a decade, computational approaches based on physics-based material models can lead to much shorter development time and higher performance materials at lower cost.

Computational approaches are predicted to reduce the development time by half using improved models and data. This modeling and simulation requires reliable data on the physical properties of materials down to the atomic and molecular interactions at the nanoscale and crystal grain defects at the micro scale—all of which affect the strength of a material. "Today such data remains spotty and of highly variable quality," according to the NIST study.[17] Air Force Systems Command and others anticipate that ICME, combined with improvements in "digital thread" (addressed later), will enable better design and both new systems and repairs and modifications.

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[14] NUWC Keyport, Custom Engineered Solutions Program Report, March 26, 2015.

[15] Committee on Integrated Computational Materials Engineering, National Research Council, "Integrated Computational Materials Engineering: A Transformational Discipline for Improved Competitiveness and National Security," 2008, p. 2.

[16] Ibid.

[17] National Institute of Standards and Technology, Material Genome Initiative, https://mgi.nist.gov.

Organizations Funding/Working on the Advances

The Department of Energy's Oak Ridge National Laboratory is using ICME for alloy development for nuclear reactors. GE claims to have cut its jet engine alloy development cycle from 15 years to 9 years by using ICME. The Air Force views its "digital thread" (addressed later in this document) effort as a key enabler of ICME, one that will allow advances like "probabilistic ICME models of components linked to manufacturing data for automated model calibration" and other ICME advances.[18]

DMSMS Application

The SMEs interviewed anticipate that the computational design of new alloys (e.g., very-high-strength, new stainless steels) that DOD can use to replace aircraft landing gear with a higher-performing new part will not only perform better, but last longer, reducing DMSMS burdens. The computational design of very sophisticated 3D weaves for applications such as composite armor is allowing very-high-strength new composites.[19] Again, the DMSMS implications can be both good (less need to repair or replace, stronger repair) and bad (may be more costly, difficult, or impossible to repair an advanced, complicated material or structure).

Exploiting ICME for DMSMS purposes may require cultural changes.[20] Informatics (the science of computer information systems and engineering of information systems) and "big data" (data sets so large or complex that traditional data-processing applications are inadequate) play an important role in achieving ICME potentials; therefore, a great deal of cooperation and agreement to single data and IT system standards will be necessary, and very difficult for DOD to achieve.[21] Data sharing, "digital thread," and exploiting big data capture and integration advances are addressed later in this document.

C. Qualification and Testing Advances

Description of Advances[22]

Qualification and testing technologies are used on replacement parts to assure their quality and fitness for use, and whether they meet all requirements. DARPA's Open Manufacturing program is promoting rapid qualification technologies that comprehensively capture, analyze, and control variability in the manufacturing process to predict the properties of resulting products.[23]

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[18] Pamela A. Kobryn, Air Force Research Laboratory, "MBE & the Aircraft Digital Thread," NIST MBE Summit, December 17, 2014.

[19] SME interview, December 2015.

[20] SME interview, November 2015.

[21] SME interviews, November 2015–January 2016.

[22] While qualification and testing advances could apply to electronic items as well, none of the interviews with electronic and integrated circuit SMEs identified any.

[23] DARPA, "Boosting Confidence in New Manufacturing Technologies," May 29, 2015, http://www.darpa.mil/news-events/2015-05-29.

Potential Impact

Qualification and testing can be very expensive and time consuming. For space systems and aircraft, flight qualification can be particularly expensive. The expense and difficulties with quality assurance are further illustrated with CFs, which are used extensively in DOD aircraft, missiles, and space systems. CF manufacturing can be very hard to replicate even within the same company and manufacturing plant. There have been cases where only one line in one plant can produce consistent CF product. If CFs are discontinued as commercial market demand shifts, or new CFs replace previous ones, significant time and costs may be required to qualify a new CF (typically some modification to legacy specifications and rarely a drop-in replacement).[24] Because of these difficulties, there have been instances of DOD organizations (sometimes with other government agencies) stockpiling two to three decades of requirements of CFs to avoid losing the supply of a CF that was about to be discontinued. While new, better CFs are available, the prohibitive cost of qualification and testing deters the switch to these new CFs.

Organization Funding/Using Technologies

Several SMEs interviewed suggested that DOD fund R&D to develop better and faster methods to reduce the cost and time needed for qualification and testing.[25] DARPA's Open Manufacturing program currently has three efforts—two focusing on metal additive processes and one on bonded composite structures:

1. The Rapid Low-Cost Additive Manufacturing effort will use first-principles and physics-based modeling to predict materials performance for direct metal laser sintering using a nickel-based super alloy powder.
2. The Titanium Fabrication effort aims to combine physics- and data-based informatics models to determine key parameters that affect the quality of large manufactured structures, such as aircraft wings.
3. The Transition Reliable Unitized Structure effort aims to develop data informatics approaches for quantification of the composite bonding process to enable adhesives alone to join composite structures.

Two manufacturing demonstration facilities have been established, one at Penn State focused on additive manufacturing and the other at the Army Research Laboratory focused on bonded composites.

DMSMS Application

A Navy DMSMS SME indicated that qualification and testing cost is expensive, that in part because it involves validating a new source of supply that may be counterfeited.[26] Additive

[24] SME interview, November 2015.

[25] SME interviews, November 2015–January 2016.

[26] Navy DMSMS workshop, November 4, 2015.

manufacturing (addressed later in detail) will require significant qualifications and testing to achieve its potential for DOD DMSMS benefit. New technologies for qualification and testing will make it quicker and cheaper for redesign, new sources of parts, and other DMSMS resolution methods.

4. Advances Improving the Cost Effectiveness of Reverse Engineering and Redesign of Integrated Circuits

A. Electronic Reverse Engineering Advances

Description of Advances

Advances in computerized axial tomography (CAT) scan use computer-processed combinations of x-ray images taken from different angles to produce cross-sectional (tomographic) images of a part. There also have been continued improvements in 3D laser digitizing such as collecting 3D laser scan data of objects from multiple orientations at rates of several thousand points per second. In addition, a DARPA program improves capability to delayer and trace circuits and automate image recognition to identify gates. Furthermore, a new tool called Derive extracts details needed for reverse engineering by deriving encoding knowledge from the assembler for existing software.

Potential Impact

New technologies and continued improvements in CAT scan, x-ray scanning, and digital scans are occurring to improve the ability to recreate designs and develop the Gerber files needed to reverse engineer microelectronics.[27] DOD tends to be on the forefront of these new developments because of its greater need to reverse engineer and redesign due to considerable DMSMS problems. Imaging software and tracking software are far ahead of 10 years ago and more advances are coming.

Organization Funding/Working on the Advances

Companies are working to improve their ability to delayer and trace circuits, automate image recognition to identify gates, and put all this together into an integrated, turnkey package. DARPA is funding some companies pursuing this, through its Integrity and Reliability of Integrated Circuits (IRIS) program:

> "Through the IRIS program, DARPA seeks to develop techniques that will provide system developers the ability to derive the function of digital, analog and mixed-signal ICs non-destructively, given limited operational specifications. These techniques will include advanced imaging and device recognition of deep sub-micron Complementary Metal–Oxide–Semiconductor (CMOS) circuits, as well as computational methods to solve the NP-complete problem of determining device connectivity. Finally, the IRIS program will produce innovative methods of device modeling and analytic processes to determine the reliability of an IC by testing a limited number of samples. The current understanding of IC aging mechanisms,

[27] Gerber files are a universal language for printed circuit board designs.

> including negative bias temperature instability (NBTI), hot carrier injection (HCI), time dependent dielectric breakdown (TDDB) and Electromigration (EM), will be leveraged to develop unique diagnostic test techniques."[28]

Stanford University and University of Utah researchers have built a tool called Derive that extracts the thousands of details needed for reverse engineering from existing software. After users input the assembly syntax for the instructions for which they want encodings, Derive automatically reverse-engineers instruction encoding knowledge from the assembler by feeding it permutations of instructions and doing equation solving on the output.[29]

The Navy has used CAT scan, x-rays, and 3D scans to determine the layout of circuits without destroying them as part of reverse engineering.[30]

The Department of Energy has funded new technology and tools that it has used to nondestructively interrogate and draw information needed out of 1980s technology-integrated circuits to generate a Gerber plot.[31]

DMSMS Application

Electronic reverse engineering is often used in replacing circuit boards that are no longer produced. The military services and offices supporting DMSMS generally have very good reengineering capabilities and stay up to date on the latest advancements in reverse engineering technology, equipment, and software.[32] For example, some DOD DMSMS SMEs have interacted with the Stanford University and University of Utah researchers involved in the development of Derive. As technological advances in electronic reverse engineering continue, the DOD DMSMS community should continue to stay cognizant of the developments and apply them where opportunities arise.[33]

B. Rapid Circuit Redesign Advances

Description of Advances

The Defense Microelectronics Activity (DMEA) continually improves its technology and tools for rapid circuit redesign. No specific, revolutionary new technologies were cited, but rather

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[28] See http://www.darpa.mil/program/integrity-and-reliability-of-integrated-circuits.

[29] Dawson R. Engler, Stanford University, and Wilson C. Hsieh, University of Utah, "DERIVE: A Tool That Automatically Reverse-Engineers Instruction Encodings," http://www.cs.utah.edu/~wilson/papers/dynamo.pdf.

[30] SME interview, November 2015.

[31] SME interview, December 2015.

[32] NUWC, Keyport, "Custom Engineered Solutions Program," March 26, 2015.

[33] SME interview, November 18, 2015.

continuous improvement in manufacturing processes that total quality management programs stress is the key to long-term success.[34]

Potential Impact

Continued improvements in rapid circuit redesign technologies enable faster, lower-cost redesign of defense systems.

Organization Funding/Working on the Advances

Recognizing that a single organization was needed to address the problems of upgrading and supporting electronic technologies for all the services, DOD established DMEA.[35] DMEA operates a sophisticated design, prototyping, and testing facility supported by more than a hundred advanced technology specialists. Continuous improvements to the technology and tools for rapid circuit redesign are made under the assumption that redesign of defense systems may generally be a better approach than replacing obsolete parts.[36]

DMEA has expertise in developing microelectronic technologies with a "one-of-a-kind technological capability and highly specialized engineering expertise to design, prototype, and test new microelectronic components and systems."[37] The services also work with companies such as MacAulay-Brown Inc. that offer redesign services for obsolete logic components in DOD systems.

DMSMS Application

These advances enable faster, lower-cost redesign of DMSMS items.

C. Emulation Technology Advances

Description of Advances

Emulation is matching existing device performance in a manner that is compatible with old software that can run on top of it. Emulation advantages include the ability to consolidate some parts and achieve a "board-level solution" so that no change is needed to documentation or test programs, and there is reduced or no need for redesign.[38] There are not many emulation technological advances on the horizon.

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[34] Many total quality management books and processes stress continuous improvement, but *Out of the Crisis*, by W. Edwards Deming, is probably the most widely cited.

[35] SME interview, November 2015.

[36] See http://www.dmea.osd.mil/home.html.

[37] Ibid.

[38] Harvey Hanson, Hoa Vo, SPAWAR Systems Center; Ken Urtel, Defense Logistics Agency; and James Crabbe, Les Avery, Sarnoff Corp., "Long Term Supportable Solutions For Complex Integrated Circuits," Commercial Technologies for Maintenance Activities (CTMA), 2005.

Potential Impact

Emulation technology has advanced from being able to provide military quality F3I microcircuits as simple as 1,000 transistors in standard devices to today's capability of emulating complex military application specific integrated circuits (ASICs) containing more than 1 million transistors. The emulation programs have saved the government hundreds of millions of dollars by avoiding costly circuit card assembly redesign efforts.[39]

Organizations Funding/Working on the Advances

The Defense Logistics Agency's (DLA's) Advanced Microcircuit Emulation (AME) program can develop and validate microcircuit emulation technology needed by DOD when private industry exits the market.[40] Once emulated, the solution is permanently available for DOD use. The AME program is the principal DOD organization that funds and works on emulation technology advances. It stays up to date on emulation technology advances to continue improving the capability to self-manufacture obsolete integrated circuits to maintain old DOD systems.

DLA's AME program staff do not see new technologies coming that will make their work easier. Indeed, they see technology advances working against them—faster circuit technology change, and faster obsolescence, and more rapid switches to new chips and technologies that make obsolescence problems faster. Many other SMEs echoed this warning that continued technological change will offer more obsolescence problems as well as some better means to address them.[41]

DMSMS Application

There may be fewer requalification demands with emulation relative to redesign, especially if software redesign is required.

The SMEs interviewed stressed that while DOD needs to stay on top of integrated circuit (IC) emulation advantages, the far more important thing to do is plan for IC chip obsolescence and either procure all future demands up front or be sure of access to all necessary technical data.[42]

D. Field Programmable Gate Array Advances

Description of Advances

Field programmable gate arrays (FPGAs) are a practical way to offer a wide variety of logic functions.

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[39] See http://www.ncms.org/wp-content/NCMS_files/CTMA/TechnologyShowcase2012/DefenseLogisticsAgencyCTMA%202012Abstract.pdf.

[40] More detail on the manufacturing aspects of this program is provided in Section 5.3.

[41] SME interviews, October 2015–January 2016.

[42] SME interview, November 2015.

While FPGAs are decades old, they continue to benefit from advances that make them increasingly valuable for DMSMS applications. Modern FPGAs are now software programmable as well as hardware programmable.[43] Advances in FPGAs have made them smaller, and there also have been improvements in the ability to program them to implement any logic and emulate most older electronics. The characteristics of capacity, speed, cost, and power have improved with technological advances since the mid-1980s. In the past 12 years, capacity has increased 50-fold and speed has increased 10-fold. Over the same period of time, price and power requirements have decreased by an order of magnitude.[44]

Potential Impact

For low-volume production, a programmable logic device is usually less expensive than a dedicated wafer ASIC run.[45] FPGAs, however, suffer from not just the normal IC obsolescence issues, but also the added difficulty and complexity of programming updates and software obsolescence.[46]

Organizations Funding/Using Technologies

Intel’s purchase of FPGA manufacturer Altera in 2015 may lead to some important DMSMS advances as aerospace and defense high-performance embedded computing systems have often paired Altera’s FPGAs with high-end Intel microprocessors. Intel’s plans and huge budget to further integrate FPGAs and microprocessors could lead to more improvements.[47]

DMSMS Application

FPGA advances will help DOD system redesigns and emulation of replacement chips. Some credit advances in FPGAs as enabling the feasible emulation of complex ASICs that DOD can no longer buy or produce starting from a high-level design file.[48] While it may seem expensive to use an FPGA with far more capability than needed for the replacement ASIC, it is usually cheaper than building a new ASIC from scratch.[49]

Unfortunately, FPGAs themselves are often subject to obsolescence. Finding a form/fit/function substitute may be an issue. Despite being programmable, intellectual property

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[43] Stephen M. (Steve) Trimberger, “Three Ages of FPGAs: A Retrospective on the First Thirty Years of FPGA Technology,” Proceedings of the IEEE, Vol. 103, No. 3, March 2015, p. 329.

[44] Ibid., p. 318.

[45] Milton Engler, SRI International, “Programmable Logic Device Obsolescence,” DMSMS 2015 Conference, December 2015.

[46] Ibid.

[47] John Keller, “Intel to boost integrated microprocessor and FPGA offerings with acquisition of Altera,” Military Aerospace website, militaryaerospace.com, June 1, 2015.

[48] Alan Baker, Winslow Adaptics, “Beating obsolescence through emulation,” Aerospace Manufacturing website, www.aero-mag.com, May 2013, p. 13.

[49] SME interview, October 26, 2015.

issues may complicate the identification of a functional substitute, even when form and fit are not problems. Nevertheless, it is generally easier to resolve FPGA DMSMS issues than ASIC issues.

E. Assembled Replacement Integrated Circuit Advances

Description of Advances

Assembled replacement integrated circuits (ARICs) are miniature printed circuit boards that combine FPGAs, complex programmable logic devices, and other components.[50]

Potential Impact

An ARIC replicates an obsolete or failed IC and can be inserted in its place.[51] Using programmable devices and a custom hardware description language code, these circuits are also more adaptable and sustainable, and easier to upgrade and improve.[52] ARICs may or may not use FPGAs.

Organizations Funding/Using Technologies

NUWC Keyport has developed ARICs. Naval Sea Systems Command (NAVSEA) has completed about six ARIC projects, mostly for NAVSEA and Air Force platforms.[53]

DMSMS Application

A key advantage of ARICs is that they avoid more complex redesigns—they are a new source for the function of the obsolete IC, but the process control block and higher-level assemblies do not need to be redesigned. The cost of developing an ARIC depends greatly on the functionality and complexity of the IC being replaced, but it is often less expensive and less risky than a larger-scale redesign for a few reasons:

- There is a reduction of new qualification testing requirements and associated changes to all documentation.
- Because reverse engineering may not provide all of the design and requirements data needed to facilitate a redesign of a single subsystem or subassembly, it may be necessary to derive that information before a new design can be finalized. This process is expensive and not foolproof.

[50] Corey Kopp, Naval Undersea Warfare Center Division, Keyport, “Assembled Replacement Integrated Circuits (ARICs),” 2015.

[51] Ibid.

[52] SME interview, October 2015.

[53] Corey Kopp, NUWC Keyport, “Assembled Replacement Integrated Circuits (ARICs),” 2015.

NAVSEA has found that keeping the old design and replacing obsolete chips with ARICs to facilitate sustainment is much cheaper and less risky.[54]

F. Interposer Advances

Description of Advances

Interposers are substrates that are used to attach components to the motherboard enabling adaptations to fix a legacy circuit board. New interposers provide better performance.[55] Silicon interposers are being used to stack chips side-by-side, allowing designers to put dies next to each other in a high-bandwidth, low-latency configuration.[56] Interposers are becoming more prevalent due to the regulatory switch to lead-free components and an unwillingness of OEMs to support legacy products.[57]

Potential Impact

Kyocera recently introduced “Advanced Package X” interposers that provide fine-pitch wiring and a small size to support 2.5D interposer requirements. They have smaller signal transmission loss compared to silicon interposers, a low warpage, and a lower cost than silicon or glass interposers.[58] While specific impacts were not covered by the SMEs, advances in interposer advances are particularly useful to DOD because of our special need to redesign and maintain obsolete electronic systems.

Organizations Funding/Working on the Advances

Outside of commercial industry, no DOD efforts have been identified.

DMSMS Application

While not a leading technology development for industry, DOD leverages interposer advances to help address its somewhat unique DMSMS demands, maintaining very old electronic systems.

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[54] Ibid.

[55] See https://www.ectc.net/files/64/5%20Thursday%20PM%20Organic%20Substrates%20Session/4%20CPMT%20Seminar%20140529%20M.%20Ishida,%20Kyocera%20WEB%20UP.pdf.

[56] See http://electroiq.com/blog/2011/06/silicon-interposers-building-blocks-for-3d-ics/.

[57] Murtrietta Circuits website, www.murrietta.com/interposer-adapters.html, viewed September 2015.

[58] See http://www.i-micronews.com/advanced-packaging-news/5026-kyocera-apx-an-advanced-organic-technology-for-2-5d-interposers-a-closer-look.html.

5. New Approaches to Dealing with Software Obsolescence and Vulnerabilities

A. Software Obsolescence Prevention Advances

Description of Advances

Advances in adaptive software systems increase the functional life of software. There are now a number of “origin analyzers” that examine software to determine if they have known obsolete or vulnerable components.

Potential Impact

Obsolescence management focuses on hardware, often ignoring software that also must be sustained and sometimes upgraded and replaced. Because many old and often unique systems are operated, DOD uses some ancient software programs. It also uses state-of-the-art software systems, such as the Joint Tactical Radio System with software-defined radio. Some FPGAs have software update and obsolescence issues.

A 2012 study estimated that 80 percent of the code in today’s applications comes from software libraries and frameworks, with the risk of vulnerabilities that enable an attacker to exploit the full privilege of the application, including accessing and stealing data and files.[59] A briefing on software obsolescence prepared for the DMSMS community recommended developing and releasing scanning tools to help DOD organizations determine what’s in use, creating standard government contract language to help guard against use of vulnerable code, and having someone in DOD take the lead in addressing this software obsolescence and the vulnerable code problems.[60]

Software is a large part of new, complex weapon systems. While the F-16 and fourth-generation fighters had 1–2 million lines of code, the F-35 has 24 million lines of code.[61] It is not just the IT systems, but the interfaces between applications and components that can pose challenging software obsolescence management problems.[62] There are significant costs for qualifying and testing any software update or issue, as well as the reprogramming costs.

As a result, software obsolescence and vulnerabilities (updating software and introducing malicious code) are a growing area of concern.

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[59] Jeff Williams and Arshan Dabirsiaghi, Aspect Security, Inc., “The Unfortunate Reality of Insecure Libraries,” March 2012.

[60] David Wheeler and Jeff Larsen, Institute for Defense Analyses, “Countering Vulnerable/Obsolete Software Libraries,” PowerPoint briefing, 2012.

[61] Joe Mueller, “Integrating Software and Hardware Obsolescence Management,” Defense Manufacturing Conference, December 2015.

[62] Ibid.

Organizations Funding/Working on the Advances

DLA's Generalized Emulation of Microcircuits (GEM) and AME programs address software obsolescence, collecting all the information on source code, software used, and related details in the technical data package for all integrated circuits (including programmable logic devices) they deal with.[63] Air Force Systems Command is supporting improvements and agility in the software change process.[64]

DARPA has financed some research to address software obsolescence management, such as its Building Resource Adaptive Software Systems (BRASS). This 4-year project investigated requirements for software systems and data to remain robust and functional for a century.[65]

BRASS has several bold objectives:

1. Reduce the time to repair vulnerabilities and port useful functionality in complex systems from human time to machine time
2. Allow various syntactic and semantic forms of adaptation to be applied over large code bases
3. Enable adaption to be generally applicable for a significant fraction of the code base making up an application and the underlying ecosystem
4. Sufficiently reduce analytics and runtime monitoring overhead to enable adaptive solutions to be effective in continuously operational, deployed environments.[66]

Carnegie Mellon professors were just awarded (in February 2016) BRASS project funding of $3 million over 4 years to "ensure that applications can seamlessly continue to operate correctly and usefully in the face of formidable challenges … and implementation of long-lived, survivable and complex software systems that are robust to changes in the physical and logical resources provided by their ecosystem."[67]

DMSMS Application

It is too early to assess the feasibility of BRASS, but it is a promising approach that the DMSMS community needs to monitor and help support. Other new means of automating software updates and guarding against the introduction of malicious code also bear watching and perhaps some active support.

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[63] Milton Diaz, SRI International, "Programmable Logic Device Obsolescence," DMSMS 2015 Conference, December 2015.

[64] SME interview, December 2015.

[65] Joe Mueller, "Integrating Software and Hardware Obsolescence Management," Defense Manufacturing Conference, December 2015.

[66] DARPA-BAA-15-36, Building Resource Adaptive Software Systems, Frequently Asked Questions, as of April 28, 2015.

[67] Carnegie Mellon University, Department of Electrical and Computer Engineering, news release, "Franchetti and researchers awarded DARPA BRASS project," February 8, 2016.

6. Advances to Assist Organic Manufacturing of Replacement Parts

A. Additive Manufacturing Advances

Description of Advances

Additive manufacturing (AM) was introduced in Section 2.1. This section elaborates on AM due to the importance of this technology for DMSMS and the advances that are being made in expanding AM applications.

Potential Impact

There are many potential applications of AM mostly related to enabling lower-cost, low-volume manufacturing for components not subject to great stress. AM can avoid many upfront production costs and achieve significant cost reductions.

One key application area is prototyping where AM has been used for years. AM enables faster prototyping by more quickly (and perhaps at lower cost) producing a small number of parts. For example, the Army used AM to produce molds for a prototype new aircrew mask. Once the design was finalized and approved, conventional manufacturing methods were used.[68] The Air Force is also using AM for prototyping.[69]

A second application area is that of castings and forgings. DLA's recent newsletter *The Innovator*, in an article by Kelly Morris, DLA R&D chief, cited AM work in this area.[70] Many SMEs interviewed also emphasized AM as especially suited for castings and forgings.[71] Metal castings are a good fit for AM. Sandcasting for AM involves printing a model, with much less variation and better features. Keyport has a machine for this.[72] DLA projected cost savings of 33–50 percent for AM casting core tooling of engine airfoils (blades and vanes).[73]

Similar benefits can be achieved for tooling applications of a small lot size. AM avoids the need for storage. In addition, AM is being used to produce special tooling instead of using machining and assembling processes to manufacture such tooling.

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[68] Government Accountability Office, "Defense Additive Manufacturing: DoD needs to systematically track Department-wide 3D printing efforts," GAO-16-56, October 2015, p. 16.

[69] Ibid., p. 21.

[70] Kelly Morris, DLA, "R&D Strategic Focus Areas Highlight Support to the Warfighter," in *The Innovator*, November/December 2015, p. 1.

[71] SME interviews, October 2015–January 2016.

[72] Liz McNichol, NAVAIR, at Navy DMSMS workshop, November 4, 2015.

[73] "DoD ManTech: Balancing National Security with Fiscal Realities," December 2014; cited in Government Accountability Office, *Defensive Additive Manufacturing Study*, 2015, p. 22.

AM also has special abilities to produce a perfect custom product, with complex internal shapes not producible via traditional, subtractive processes. For example, General Electric produced a one-piece fuel nozzle through AM in a metal super alloy that previously required two dozen individual parts that were then furnace brazed into a final component with old technologies.[74] There is no disagreement that oddly shaped, small, and low-stress plastic parts are an important AM application. AM enables both a better, more exact fit and cost savings.

These selective uses of AM where there are significant advantages over traditional manufacturing have important DMSMS implications. While the scope of AM applications will expand, it is not likely to be as broad as some advocates have stated. The claim of deliberately abandoning large production runs and stockpiled inventories is not likely—it will still be cheaper to mass produce with traditional manufacturing and keep inventories for the vast majority of parts. For example, it will likely never make sense to produce standard screws and manhole covers with AM. AM has many advantages, but is unlikely to replace most traditionally manufactured, mass-produced, high-volume, low-unit-cost parts.[75]

DOD will have far more constraints, difficulties, and higher costs using AM as its systems must meet more rigorous conditions and standards and the military is more risk averse in tolerating failures. Commercial applications may also be constrained if risks considered acceptable by manufacturers and consumers result in lawsuits due to AM part failures occurring.

There also are a number of other AM challenges that are affecting its widespread adoption. The surface finish of AM parts is often not as good as (rougher than) machined surfaces. Also, the lack of uniform mechanical properties, in particular, is a serious constraint for DOD where strength, weight, and highly reliable quality are critical. A limitation of AM that will decrease over time is the relatively small number of materials available for sophisticated AM.[76] AM has very limited applicability to microelectronics, at least for the next decade.

In a 2013 memo, Dr. Lewis Sloter warned that "the greatest research challenge is the need for objective in-process control and monitoring of AM processing in order to confidently provide reliable and reproducible properties in the final product."[77] That issue was reinforced by a 2015 Government Accountability Office report, which pointed out that "ensuring that manufacturers can repeatedly make the same part and meet precision and consistent performance standards" is a key challenge.[78]

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[74] Lewis Sloter, OASD(R&E), "Potential Defense Science Board Study on Additive Manufacturing," Memo, August 19, 2013, p. 2.

[75] SME interviews, October 2015–January 2016.

[76] SME Interview, October 2015.

[77] Lewis Sloter, OASD(R&E), "Potential Defense Science Board Study on Additive Manufacturing," Memo, August 19, 2013, p. 5.

[78] Government Accountability Office, "Defense Additive Manufacturing: DoD needs to systematically track Department-wide 3D printing efforts," GAO-16-56, October 2015, p. 9.

Metal AM has significant problems because the microstructure of the material can be very different from traditional manufacturing processes, and far more variable. For parts that are not under great stress or do not play a critical role in a system, this may not matter, but grain structure and property differences from traditional manufacturing and the higher variability and uncertainty in AM metal parts are significant drawbacks for many DOD applications.[79] For critical parts, such as aircraft engine stressed components, metal AM may not be usable. The parts might perform adequately, but few would be willing to take the risk. The SMEs estimated that it may take a decade to achieve confidence and certification for some AM metal applications.

Contrary to expectations, testing of AM parts for strength and other properties is neither simple nor fast. Because of the tremendous variation possible in AM metal fabrication, which in effect involves thousands of “mini melt pools” in a single part, there is huge potential for variability and potential property problems.[80] The grain structure and property certification problems for metal AM will likely take many years to rectify—and may be a long-term barrier to AM metal replacement parts for high-stress, critical components. The fact that an AM metal or polymer part may look the same, but have far different properties and potentially much lower strength and durability, may yield another big realm for dangerous counterfeit parts. They may have cheap material inside, with the proper material just as a coating, or have voids and defects. Several SMEs interviewed stressed that there are overly optimistic expectations for AM metal use and significant problems due to what may be inherent variance in so many millions of tiny welds that make up big metal AM products.[81]

There is a need to test and certify AM applications. Metal AM poses greater challenges to ensure that the metallic AM process meets specifications. Forging, rolling, and traditional metal manufacturing and processing yield far more consistent properties and often better alignment and grain structure.[82] For example, when industry develops a new alloy, even with very old, proven production processes, it can take more than 5 years and several million dollars to qualify the alloy. For metal AM with more variability and less experience, it will likely take longer.[83] Pratt & Whitney’s president of aftermarket predicts that maintenance, repair, and overhaul shops in the future will “print” the parts they need with additive manufacturing technologies, speeding up repair tasks and reducing stored inventory. “It will work. It will be efficient. It’s the way the industry will go,” the executive said at an Aviation Week conference in 2014. But the *Aviation Week* article covering this promotion of AM warned that “it is not clear how quickly the nascent technology will take over, particularly for safety-critical parts where certification hurdles remain.”[84]

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79 SME interviews, November 2015–January 2016.

80 SME interview, November 2015.

81 SME interviews, October 2015–January 2016.

82 SME interviews, November 2015–December 2015.

83 SME interview, November 2015.

84 See http://aviationweek.com/mro/pratt-whitney-predicts-additive-manufacturing-every-shop.

The December 2015 DMSMS Conference identified some challenges and, for now at least, significant constraints on additive manufacturing (as shown in Table 3).

Table 3. Additive Manufacturing Challenges and Constraints to Widespread Adoption

Need/Issue	Impact If Not Addressed
– Dimensional accuracy and surface finish	– Additional processing cost, unusable parts
– Uniform mechanical properties—different in build direction	– Increased design complexity and added weight, suboptimal designs
– Improved process control and repeatability	– Acceptable part quality, process yield and cost
– Non-destructive evaluation methods for complex defects and part geometry—understanding of potential defects, effects of defects	– Undetected defects leading to component failure
– AM standards (materials, process, machine, quality)	– Slow implementation of AM in industrial base
– Qualification and certification protocols	– Slow adoption, conflicting approaches, waste in research and sustainment dollars
– Design tools for AM components	– Suboptimal design, increased time to market, material waste, poor performance

Source: Edward Morris, National Center for Defense Manufacturing & Machining, "Manufacturing: Redefining the Future," PowerPoint presentation at DMSMS Conference, December 2015.

Organizations Funding/Working on the Advances

The Navy is collaborating with AM organizations in DOD and elsewhere in government. The Navy's initial AM focus is on addressing obsolescence issues—not new systems production. Air Force Systems Command engineers consider AM for electronics to have great potential. Additively printing a circuit board with embedded sensors, electronics embedded in parts, and other AM electronics are envisioned for Air Force applications.[85]

NUWC Keyport is one of many DOD organizations using AM to replace obsolete parts as well as for repair, testing and evaluation, and upgrades. NUWC Keyport works on obsolescence issues for electronic, mechanical, and electro-mechanical products, using AM extensively on both new design and redesign projects.[86] A variety of polymer AM processes are used as well as two direct metal AM processes: direct metal laser sintering and direct energy deposition. AM has led to some reduced inventory levels and inventory cost savings. Polymer AM has been used for over

[85] SME interview, December 2015.

[86] Naval Undersea Warfare Center, Keyport, "Custom Engineered Solutions Program," March 26, 2015.

a decade. Keyport alone has 3D-printed about 40,000 components.[87] The Agile Manufacturing Center for Casting Technologies, also at NUWC Keyport, can make castings faster and cheaper with AM. They can often be made better as well, though there are size limits with current AM machines.[88]

General Electric's fuel nozzle for the new Leap turbofan engine that will power the Boeing 737MAX and Airbus A320NEO is an often cited example of AM success. This single-part additive fuel nozzle replaces a legacy fuel nozzle that required 20 separate pieces welded and assembled together. The AM part also weighs 25 percent less. The company expects to move into full production of Leap nozzles, with 50 to 100 additive machines producing 40,000 nozzles per year by 2020. This fuel nozzle is one of the thousands of parts in a jet engine.[89] This widely cited success may be misleading if it is interpreted as great potential for AM in highly advanced, critical component replacement for things such as jet engines (where the opposite conclusion is more likely for the near term). This was a case of exploiting an especially suitable AM application. The fact that other thousands of parts are not produced by AM may be an indication of how limited the AM potential is, rather than a sign that it will replace subtractive manufacturing.

The National Center for Defense Manufacturing and Machining (NCDMM) was selected to manage the National Additive Manufacturing Innovation Institute, the pilot institute for the National Network for Manufacturing Innovation in 2012.[90] These institutes will bring together industry, universities, and federal and state agencies to accelerate innovation by investing in industrially relevant manufacturing technologies with broad applications. Their goal is to bridge the gap between basic research and product development. Funding for these R&D projects totals \$30 million of federal funding and \$39 million from industry and a few states.[91] In 2012, the National Network for Manufacturing Innovation sponsored a pilot factory for AM at NCDMM, supported by DOD.[92] As of 2015, the Air Force Research Laboratory (AFRL) manages the "America Makes" AM initiative, and it is the lead for DOD in this \$60 million, government-funded AM initiative.[93]

The current focus of much AM R&D is on certification processes, processing characteristics, and performance of products so they can be certified. This is not just driven by the regulatory need

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[87] SME interview, October 2015.

[88] SME interview, October 2015.

[89] See http://aviationweek.com/mro/pratt-whitney-predicts-additive-manufacturing-every-shop.

[90] National Center for Defense Manufacturing and Machining, "NCDMM is Chosen to Manage National Additive Manufacturing Innovation Institute," press release, August 16, 2012.

[91] Ibid.

[92] Lewis Sloter, OASD(R&E), "Potential Defense Science Board Study on Additive Manufacturing," Memo, August 19, 2013, p. 3.

[93] Government Accountability Office, "Defense Additive Manufacturing: DoD needs to systematically track Department-wide 3D printing efforts," GAO-16-56, October 2015, p. 7; Robin Brown, Jim Davis, Mark Dobson, Duane Mallicoat, "3D Printing: How Much Will It Improve the DoD Supply Chain of the Future?" *Defense AT&L*, May–June 2014.

to certify, but because quality and component strength may not be as good as compared to "subtractive" manufacturing techniques. The Joint Technology Exchange Group is conducting R&D in this area.[94] While subject to high heat stress, GE's fuel nozzle has relatively little physical stress, therefore certification requirements are not demanding.[95] As of 2015, NIST is funding research to provide quality assurance of AM parts.[96] DOD has a specialized working group for standards and processes for material, process, and product qualifications for AM—the DOD Metals Additive Manufacturing Qualification and Certification Working Group.[97] There are other service AM coordination groups.[98]

DLA lists AM as a priority in its "R&D Strategic Directive." In a 2015 slide presentation, 3D printing is featured with the description "Store data, not parts."[99] While storing data is generally a good idea, the cost advantages of mass-produced, traditionally manufactured parts, and the relative ease of pulling a part out of inventory rather than additively manufacturing it when needed, make this a questionable proposition. The ability to do AM successfully does not mean it is cost effective compared to large-volume traditional manufacturing and part stockpiling. Also, because AM technology is evolving so rapidly, technical data formats are changing as well.

DMSMS Application

The technology most cited as a boon for DMSMS is additive manufacturing. But at least six different DMSMS material and technology SMEs interviewed stressed that there are limitations on what AM can offer, and it even poses some risks for DMSMS.[100] The scenarios below indicate applications where a DOD DMSMS practitioner may be able to leverage AM for a DMSMS resolution.

- *Manufacturing support tooling not available to make a part.* AM may have particular importance in supporting mechanical obsolescence where the tooling used to make the original part is no longer available (lost, thrown away, etc.). AM would take the place of castings and/or forgings where only a few parts are required. This may represent the best cost-value condition by which it makes sense (cost avoidance) and timing (reduced acquisition time) to use AM versus the traditional manufacturing process.
- *Rapid response tooling.* AM may have particular benefits for tooling applications where a rapid unique geometry response is required. In many cases a suitable AM

[94] SME interview, October 2015.

[95] Ibid.

[96] Government Accountability Office, "Defense Additive Manufacturing: DoD needs to systematically track Department-wide 3D printing efforts," GAO-16-56, October 2015, p. 9.

[97] Ibid., p. 26.

[98] Ibid., p. 27.

[99] Kelly Morris, DLA, "DLA Research and Development Program," PowerPoint briefing, June 17, 2015, slide 7.

[100] SME interviews, October 2015–January 2016.

tooling may be produced within several weeks after the first requirement is communicated to the AM manufacturing source. If, for example, a DMSMS situation occurs where the original tooling is no longer available and the original manufacturing method (generally machining) can no longer be accessed, then AM can relatively rapidly duplicate and even improve the original tooling.

- *Technical data package (TDP) not available.* If the TDP is no longer available and/or the OEM is not willing or able to remake parts, then DOD would naturally be required to regenerate the TDP (including 3D models). Once these models have been created, it would be natural to consider using AM to manufacture these parts as AM can leverage these newly created 3D models. Per the statement that AM is not as cost effective as traditional processes, this is true especially if 3D models do not exist. However, once the 3D models exist, then that cost difference may be quite less and, depending upon quantities required, may actually favor AM.
- *Low manufacturing quantities.* AM is particularly favorable cost-wise for parts where DOD requires a limited supply (generally fewer than 200 or so parts as an estimate). The non-recurring engineering costs to start up a casting or forging process for low quantities of parts may be a significant portion of the overall manufacturing cost for low-quantity parts. Hence, DOD vendor quotes are often very high cost because their NRE is relatively high due to the low volume of parts requested by DOD. There are several scenarios where the ability to make highly customized and/or low-volume replacement parts is important for DOD:
  - Manufacturing an urgently needed part in the field or at sea. The Navy has used AM on submarines, in one case manufacturing circuit card slips for servers because they were no longer produced.[101]
  - Field production of parts that are not obsolete. This can avoid the need to store or move the parts in theater, reducing the logistics/transportation demands and allowing faster replacement.[102]
  - Rapid production of a few replacement parts for deployed forces. Some experts expect a relatively constant rate of improvement in capability and use of AM for sustainment over the next decade, to the point where DOD can design, process control, produce, and certify most replacement parts or retrofit old parts with new items that have the same form, fit, and function, with AM. Other SMEs believe that certification will be a long-term problem for AM.[103]

[101] Government Accountability Office, "Defense Additive Manufacturing: DoD needs to systematically track Department-wide 3D printing efforts," GAO-16-56, October 2015, p. 13.

[102] Ibid.

[103] SME interview, October 2015.

- *Shortened lead times to build, test, and validate substitute items used to resolve DMSMS issues.* The Air Force is investigating ways to partner with industry to establish innovation centers that would reduce the lead times for building, testing, and validating substitute items used to resolve DMSMS issues through the use of additive manufacturing concepts. The Air Force issued a request for information in February 2016 and held partnership symposiums at potential sites. These innovation centers are planned to be a turn-key capability to design, test, qualify, and produce the parts it needs so that it can avoid the pitfalls that come with obsolescence.[104]

Another reason that AM in theory is important to DMSMS is that once the detailed data on a part has been obtained—there is no real obsolescence problem in the future—AM can be used to produce the item decades later when it is needed.[105] NUWC Keyport estimated that polymer and metal AM might be feasible for 5 to 10 percent of demand within the next 10 years.[106] In these ideal AM applications, NUWC Keyport has achieved order of magnitude improvements in cost and schedule.

AM is not, however, a panacea for all DMSMS issues. As noted earlier, for high-stress metal applications where the "mini-melt" welding approach is used in lieu of traditional forging, AM can yield a weaker part of uncertain quality. A second risk of AM is that the attractions of much cheaper, simpler equipment for AM relative to traditional manufacturing will make it easier to counterfeit and open up a wider range of products to counterfeiters. Finally, DOD must be careful not to overly rely on AM for sparing and consequently cut back on spares production and stockpiles. This will lead to more DMSMS issues and more opportunities for counterfeits and malicious insertions. Furthermore, traditional manufacturing of spares will likely retain a significant cost advantage for most DOD items for the foreseeable future.

B. High-Speed Machining Advances

Description of Advances

There are continued improvements in high-speed machining technologies and computer-controlled machines.[107] Improvements in information technology, robotics, and computer numerically controlled machines continue to aid traditional, subtractive manufacturing methods.

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[104] Courtney Albon, "Sustainment Innovation Centers Could Help Address Parts Obsolescence," *Inside the Air Force*, March 25, 2016.

[105] AM involves a huge digital database management requirement that could be a problem for DOD. AM works from a digital model that could be the solution to many obsolescence problems, because the data could be stored and the item could be produced much later when needed. But as addressed later in Section 6.5, DOD is particularly ill suited for a totally standardized, completely integrated, single data system.

[106] SME interview, October 2015.

[107] SME interviews, January 2016

Potential Impact

Despite the emphasis on AM, improvements in traditional metal manufacturing and high-speed machining (subtractive manufacturing) will be important, perhaps indefinitely, given AM metal quality and reliability limitations.

Organizations Funding/Working on the Advances

Private industry is pursing gradual advances, rather than DOD and organic manufacturing.

DMSMS Application

Because of what may prove to be inherent problems with metal AM, DOD DMSMS may want to emphasize the consideration of advanced, high-speed machining technologies.[108] By using traditional, reliably manufactured metals and subtractive processing, the material strength and properties can be assured, and certification would be much easier.

C. Analog/Linear Microcircuit Emulation Production Advances

Description of Advances

DLA's AME and GEM programs continually adopt new technologies and advances to improve DOD's ability to self-manufacture low-volume, obsolete integrated circuits needed to sustain old systems. A current area of emphasis is analog/linear microcircuit advances.

Potential Impact

Under decades-old relationships with Sarnoff Corporation and the GEM program, there is limited, trusted production capability (design, fabricate, package, and test) for producing and repairing both legacy and new weapon systems. With continual technology updates and improvements, the GEM program ensures that the microcircuit emulation contractor can sustain DOD production of obsolete chips that commercial industry has abandoned.[109]

As the electronics industry constantly pursues faster circuits with lower power, transistors have to be smaller and closer together, with smaller and smaller "wiring" and feature sizes. The AME and GEM programs must follow suit (though with older technology). Over the past 5–7 years, the AME program has been implementing the basic 0.8 micron technology for GEM program production while also developing 0.5 micron feature-size technology. DLA will spend the next 5–7 years implementing 0.5 micron into production capabilities while developing 0.35 micron technology.[110]

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[108] SME interview, November 2015.

[109] Alan Clark, DLA, "DLA DMSMS Program," PowerPoint briefing, November 5, 2015.

[110] Ibid.

Organizations Funding/Working on the Advances

DLA is funding the R&D in this area. There have been joint efforts with other services in the past, but there are none presently.[111]

DLA's GEM and AME programs have been emulating digital microcircuits, in association with Sarnoff, almost exclusively to provide options to satisfy the ongoing demand for those discontinued technologies. DLA's GEM program "provides a permanent solution to the problem of microelectronics obsolescence."[112] While DLA developed GEM more than 25 years ago, microelectronics obsolescence remains a recurring, expensive problem that many SMEs interviewed insist will grow worse due to continued technological change.[113] The AME program is over a decade old. Its objective is to "develop, demonstrate and prove low rate production capability for advanced microcircuit technology, provide an ongoing rapid, economical, high quality microcircuit emulation capability ... [of] form, fit and function equivalent microcircuits."[114] Sarnoff won the contract to run AME.[115] AME is responsible for R&D, GEM is responsible for production. AME develops new manufacturing technologies and capability (selected in consultation with GEM), and GEM uses it to emulate individual part types.

The AME program recently began developing analog/linear microcircuit emulation capabilities for the GEM program to provide a form, fit, and function replacement part in order to maintain the existing physical configuration of the next-higher-assembly (NHA), thus avoiding the cost to redesign the NHA. This also reduces the impact on weapon system readiness during the time it would take to redesign. The first analog/linear capability will transition to production (GEM) in about 4 years. Digital will continue to transition new capabilities yearly.[116]

DMSMS Application

Self-manufacture of chips that industry no longer produces is a vital part of DOD's DMSMS capability. Maintaining and improving AME and GEM production capacities is essential for DOD to produce obsolete integrated circuits to keep old DOD systems in operation.

D. Die Extraction/Reassembly Advances

Description of Advances

Die extraction/reassembly takes functionally suitable commercial ICs that are not ruggedized or certified for military use (or have questionable sourcing), extracts the die (circuit), screens them

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[111] Ibid.

[112] SRI International website, sri.com.

[113] SME interviews, November 2015–January 2016.

[114] Harvey Hanson, Hoa Vo, SPAWAR Systems Center; Ken Urtel, DLA; James Crabbe, Les Avery, Sarnoff Corp., "Long Term Supportable Solutions For Complex Integrated Circuits," CTMA, 2005.

[115] Ibid.

[116] SME interview, December 2015.

for counterfeit or Trojan components, and then reassembles them into a rugged, ceramic package as a drop-in replacement for a military system.

Potential Impact

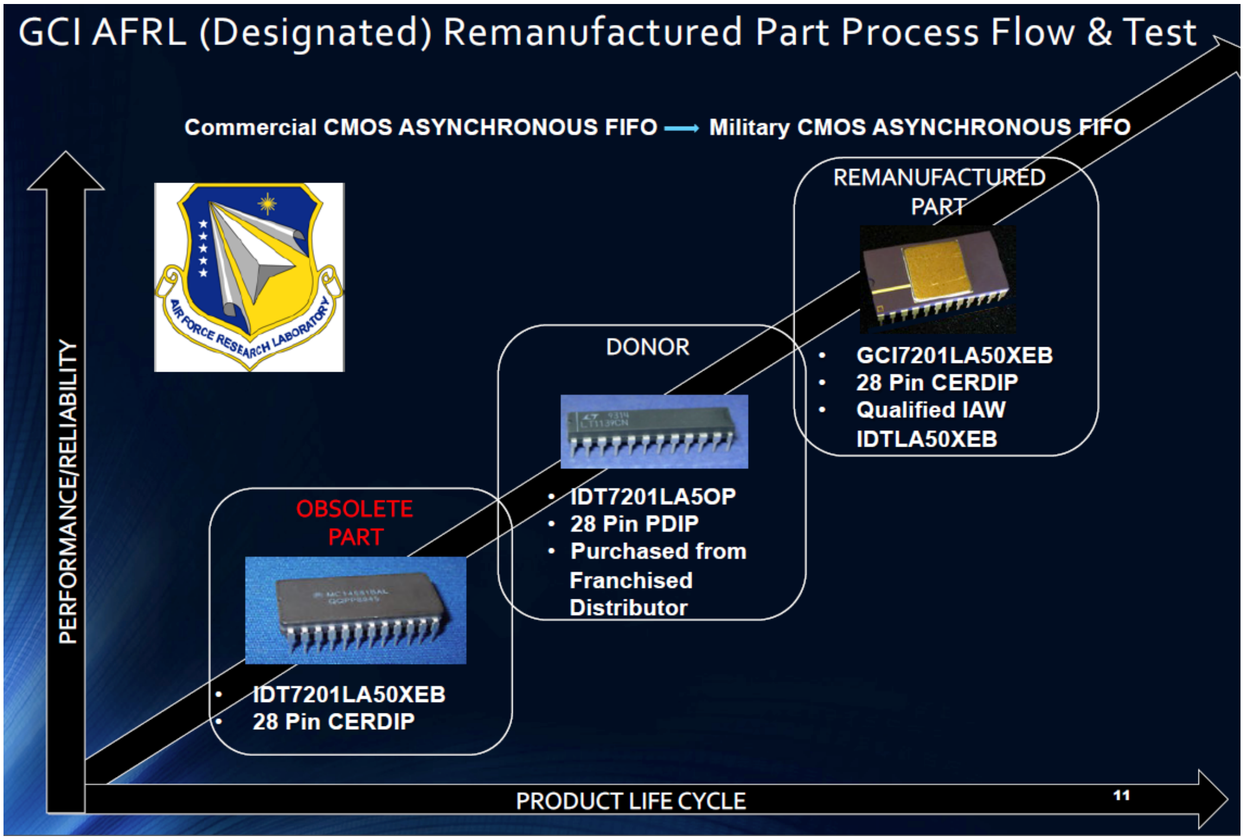
This process may save time and should save a substantial amount of money relative to the redesign and test of replacement ICs.

Organizations Funding/Working on the Advances

A relatively new, small company was formed to leverage commercial die extraction techniques for dealing with obsolete ICs.[117] It works with another company, a DLA-certified laboratory, to have its remanufactured, die-extracted, reassembled ICs tested and certified.[118] This process has been used for Teledyne Microelectronic Technologies and AFRL. As Figure 1 shows, an obsolete chip (lower left) is replaced by a non-rugged/improper fit chip (center) that has its die extracted and remounted on a ruggedized chip (upper right) that fits the DOD system.

[117] Erick Spory, Doug Schweitzer, Ed Odette, "Die Extraction/Reassembly (DER): A Potential Quick Reaction and Low-Cost Readiness Approach to Solve Integrated Circuit Diminishing Manufacturing Sources Material Shortages," DMSMS 2015 Conference, December 3, 2015, slide 3.

[118] Ibid., slides 6–13.



Source: Erick Spory, Doug Schweitzer, Ed Odette, "Die Extraction/Reassembly (DER): A Potential Quick Reaction and Low-Cost Readiness Approach to Solve Integrated Circuit Diminishing Manufacturing Sources Material Shortages," PowerPoint presentation at DMSMS 2015 Conference, December 3, 2015, slide 10.

Figure 1. Extraction/Reassembly Process

DMSMS Application

In addition to reducing resolution time and cost, this approach can provide another source of supply for obsolete ICs.

E. Multi-Beam Technology Advances

Description of Advances

Commercial ICs are fabricated using optical lithography by exposing a photosensitized silicon wafer to a pattern generated by ultra-violet (UV) laser light shining through a photomask. Each step of fabricating the transistors and interconnected layers requires its own mask. Multi-beam technology uses multiple electron beams to replace optical lithography in both the fabrication of masks and the fabrication of integrated circuits.

Potential Impact

Special facilities, called mask shops, prepare masks by writing the pattern with an electron beam. A state-of-the-art mask can take 18 to 72 hours of electron beam writing, and it can easily cost over a million dollars. A complete mask set needed to fabricate an IC can have 40 to 70 masks

and costs tens of millions of dollars.[119] A multi-beam mask writer would bring mask write times to more acceptable levels, and the cost of leading-edge masks down. A multi-beam mask writing tool is expected to be commercially available in 2 to 3 years.

The fabs that fabricate today's ICs service high-volume customers. Manufacturing the small volumes needed by DOD is simply not cost effective and is disruptive to the process flow. There are smaller specialty fabs that focus on smaller orders and process smaller, 200 mm (8-inch) wafers. Equipment manufacturers, however, do not develop and sell their latest tools in versions that process smaller wafers. To process wafers with leading-edge technology, these fabs would have to invest in the same tools as the high-volume fabs—a prohibitive expense. Multi-beam mask writers may make maskless electron beam lithography economically viable.

Organizations Funding/Working on the Advances

DARPA funded KLA-Tencor[120] (in the U.S.) to develop a multi-beam wafer writer. KLA's approach, called reflective electron beam lithography,[121] was to use a dynamic pattern generator to control an array of electron beams in a single column. After investing about $162 million of its own funds and an additional $63 million from DARPA, KLA abandoned the effort in March 2014.[122]

Multibeam Corporation (U.S.) is developing a tool for complementary E-beam lithography, which uses optical lithography to pattern a field of lines, and electron beams to cut the lines at the appropriate locations.[123] The Air Force Research Laboratory, the Defense Threat Reduction Agency, and the Space and Missile Systems Center have been funding Multibeam.[124]

MAPPER Lithography (Netherlands) was working on a 13,000-beam wafer writing tool with the research organization CAE-LETI (France). MAPPER last published papers at the Alternative Lithographic Technologies conference in 2015.[125] It did not present any papers at the 2016 conference. An industry SME described MAPPER as "dead man walking."

Vistec Electron Beam GmbH (Germany) manufactures a series of electron beam wafer writers for research and prototyping.[126] The Vistec e-beam tools use a character projection system

[119] Your Voice Matters, eBeam Initiative 2015 Survey, http://www.ebeam.org/docs/ebeam_survey_results_2015.pdf.

[120] On October 21, 2015, Lam Research announced that it will acquire KLA-Tencor.

[121] Mark McCord, et al., "REBL: Design progress toward a 16 nm half-pitch maskless projection electron beam lithography," Alternative Lithographic Technologies IV, *Proc. SPIE*, Vol. 8323, p. 832311-1, 2012.

[122] Source: Dennis Ralston, senior director, Cooperative R&D, KLA-Tencor.

[123] Multibeam press release, November 19, 2015; interview by Mark LaPedus of Semiconductor Engineering, http://www.multibeamcorp.com/PR_SE20151119.htm.

[124] AFRL Space Electronics Technology Program, January 27, 2015, slide 13; http://www.aerospace.org/wp-content/uploads/conferences/MRQW2015/7B_Mounce.pdf.

[125] *Proc. SPIE* 9423, Alternative Lithographic Technologies VII.

[126] See http://www.vistec-semi.com/products-applications/products/.

where a stencil sets the shape of the electron beam. The primary drawback of the Vistec tool set is that the stencil limits the patterns that the tool can draw efficiently.

IMS Nanofabrication (Austria) was partnering with electron microscope manufacturer JOEL (Japan) to develop a beam mask writer based on a programmable aperture plate system that controls each beam.[127] IMS had a 3-year lead on industry rivals but ran short on funding, which slowed its progress. In March 2016, Intel, an early investor in IMS, stepped in and quietly acquired IMS, which will remain a standalone subsidiary of Intel.[128] Intel is supplying its data path technology to IMS. IMS technology is very promising for mask writing, and it may be extensible to direct wafer write.

NuFlare (Japan) is the leading supplier of electron beam writing tools to the mask industry. It is developing technology that is very similar to IMS's approach—the original patents have expired. NuFlare is also using Intel's data path technology.

Avantest (Japan) is developing a 16-column wafer writer using the character and a variable shaped beam approach.[129] Intel has purchased two Avantest tools for prototyping, and CAE-LETI has acquired one for research.

DMSMS Application

Multi-beam lithography can address the "manufacturing sources" aspect of DMSMS. It can make low-volume production more accessible by enabling more facilities to afford key production equipment necessary to support more advanced IC nodes.

1. It eliminates the need for photomasks, which cost millions of dollars per set and make low-volume runs not economical.
2. Only one trusted merchant mask shop remains. Without the need for masks, multi-beam minimizes this vulnerability.
3. It enables fabrication facilities currently limited by lithography equipment availability and cost to fabricate ICs at nodes they currently cannot.
4. If a multi-beam mask writer becomes available, it could readily pattern 6-inch wafers at extremely fine nodes. This could directly address DMSMS concerns, and it should be monitored and explored further as an option.

Using multi-beam lithography to produce legacy ICs that the original vendor no longer produces will depend to a large part on the availability of the original design files. Without the

[127] Elmar Platzgummer, "Recent Progress of Electron Multi-Beam Mask Writer," eBeam Initiative Meeting at BACUS, September 29, 2015, http://www.ebeam.org/docs/ebeam_elmar_platzgummer_handout.pdf.

[128] Mark LaPedus, "The Week in Review: Manufacturing," March 11, 2015, http://semiengineering.com/the-week-in-review-manufacturing-103/.

[129] See https://www.advantest.com/products/e-beam-lithography.

design information, engineers will have to reverse engineer samples of the legacy ICs, a destructive process that is both very expensive and time-consuming.

F. Direct Write Laser Technology Advances

Description of Advances

Direct write laser technology is used to produce masks for the lower-resolution layer of ICs and to produce masks for flat-panel displays. Direct write laser technology could pattern a wafer directly without the need for a mask. This technology, however, is only applicable to fairly coarse-resolution ICs. This laser wavelength would be limited to about a 200 nm feature size. Though lower-wavelength lasers are available, they require expensive exotic optics.

Potential Impact

Direct laser write would eliminate the need for masks and would support affordable, low-volume production. The utility of this approach, however, is limited by the minimum feature size possible, which is too coarse for most applications and is on the level of IC lithography in the 1970s.

Organizations Funding/Working on the Advances

A number of companies used to make direct laser write tools for mask making. Because masks have features that are four times as course as the corresponding feature on a wafer, these tools could support masks down to 90 nm. Most, like Micronics Laser Systems (Sweden) (now Mycronic), have discontinued making tools for semiconductor masks. Heidelberg Instruments (Germany) still makes tools both for direct writing on wafers and for mask making. These tools use laser diode light sources in the low 400 nm range, and they are limited to a 500 nm feature size. Most companies have switched to supporting mask making for flat-panel displays. These masks are used in a 1:1 printing mode, with no reduction.

DMSMS Application

This technology has a low level of applicability to the DMSMS community, because of the limitations on feature sizes that it can print. The utility would increase if the technology could achieve finer feature-size capability.

7. R&D Advances Enabling Improved DMSMS Management

A. DMSMS Cost Estimation Advances

Description of Advances

DMSMS resolution cost projections are based on techniques to forecast when DMSMS issues will occur, the types of resolutions needed, and factors for estimating the cost of those resolutions. Cost estimation advances involve improved analytical techniques for performing those functions and integrating those techniques into cost estimating and DMSMS management tools.

Potential Impact

DMSMS cost estimation tools are used to forecast future DMSMS resolution costs. They may be used to develop a DMSMS component of life-cycle cost estimates, or they may be used to develop and defend budgeting and programming estimates.

Organizations Funding/Working on the Advances

A Small Business Innovation Research (SBIR) grant to Frontier Technology Inc. (FTI) helped fund a new release (version 8.1.13) of the Integrated Cost Estimating (ICE) tool with an improved parts obsolescence calculator, based on DMEA studies and the 2015 version of SD-22. Cost analysts can use default mitigation strategies and cost factors in ICE (e.g., life-of-need buy, use of an approved replacement part, or simple substitute) or enter their own obsolescence resolution plans and cost data. ICE costing is usually done at a subsystem or component level with cost models appropriate for that level. The "box level" is often used for obsolescence analysis of electronic components. Analysts can enter in obsolescence cost strategies and data down to the individual part level if desired. This can include replacement part costs, nonrecurring engineering costs, repair costs, redesign costs, and so forth. For circuit redesigns, cost data from the SEER-H[130] model is available. These obsolescence resolution costs are linked to a specific part in the system and can be put in the appropriate phase or phases of the system life cycle.[131]

Because all of the data and assumptions needed to calculate obsolescence costs must be input by the user (unless default data are accepted), this effort does not provide substantially new capability to the DMSMS practitioner who has some experience developing DMSMS programming and budgeting estimates. This version of ICE is not integrated with the University of Maryland's Mitigation of Obsolescence Cost Analysis (MOCA) software. Such an integration

[130] SEER-H is "SEER for Hardware, Electronics, & Systems," a costing and decision-support tool to estimate total cost of ownership from Galorath.

[131] David Wood, "Integrated Cost Estimation (ICE) Training," Frontier Technology Inc., March 2015; and e-mail, September 2015.

would provide greater benefit to the DMSMS practitioner. FTI hopes to get another SBIR grant to integrate with MOCA for the next release of ICE.[132]

ICE's improved parts obsolescence cost-estimating module may encourage and help cost modelers do a better job of considering obsolescence costs and including these likely expenses in life-cycle cost estimates.

NUWC Keyport, working with the University of Washington, developed several tools to help forecast, better manage, and budget for obsolescence issues.[133] Using the Obsolescence Management Information System, they developed a forecasting method based on mean end of life for a product. This study noted that changing technologies and shorter lifestyles are going to make obsolescence management more difficult.[134] Another Keyport study showed the use of graph theory to help identify complex relationships that affect cost and impacts of an obsolete part, note the most cost-effective mitigation strategy, and improve earlier identification of potential obsolescence problems.[135]

DMSMS Application

Advances in cost estimation techniques and tools can aid DMSMS management by enabling obsolescence to be more explicitly considered and rigorously modeled.[136]

B. Designing for DMSMS Advances

Description of Advances

Advances in designing for DMSMS are aimed at reducing DMSMS risk for new systems through improving the interface between DMSMS and CAD tools to explicitly consider where the part is in its life cycle, whether the part is currently obsolete, and potential substitutes.

Potential Impact

The DMSMS "Guidebook of Best Practices," SD-22, cited the example of the Virginia-class submarine program that made a special effort to integrate DMSMS considerations into the design-

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[132] SME interview, October 2015.

[133] Kristin Arney and Christina Mastrangelo, University of Washington, and Dennis Summers, NUWC Keyport, "Network Representation and Visualization to Assess Obsolescence Issues," DMSMS 2015 Conference, December 2015.

[134] Kristin Arney and Christina Mastrangelo, University of Washington, and Dennis Summers, NUWC Keyport, "Forecasting Electronic Part Lifetimes Using the Shape of the Product Life Cycle Curve," DMSMS 2015 Conference, December 2015.

[135] Dennis Summers, NUWC Keyport, "Graphs and Obsolescence Management," DMSMS 2015 Conference, December 2015.

[136] SME interview, November 2015.

build process, addressing more than 1,260 obsolescence issues with $159 million in documented cost avoidance savings as a result.[137]

Organizations Funding/Working on the Advances

The Air Force's Manufacturing Technology (ManTech) program initiates "quick-hitting, demonstration-oriented Rapid Response Process Initiative (R2PI) efforts, and incorporates the results in pilot demonstrations which focus on stimulating advanced industrial practices."[138] An AFRL SME described "designing for DMSMS" work that has been evolving for several years as a way to improve the interface between DMSMS and CAD tools, helping to consider and (where possible) design in fewer DMSMS risks in new systems.[139] Specifics of the project are summarized below:

- The intent was to conduct a study to identify tools to help engineers early in the design and then determine how to integrate into CAD design tools considering feasibility and file outputs of DMSMS tools.
- The premise is that the interface between DMSMS tool outputs and CAD tools would
  – enable engineers to access a catalog of parts to choose from for their designs and those parts could be coded red/yellow/green related to the DMSMS risk; and/or
  – enable an engineer to run an analysis on a design to identify if there is any DMSMS risk in the design and where such risk is.[140]
- ManTech plans to leverage a 3-year, $4 million manufacturing process driven design project that started in September 2015 by performing use cases at various companies on the savings generated if production information (from Georgia Tech University) were given to designers at different periods within the design process.[141]

DMSMS Application

There is widespread recognition of the need to use improved engineering methods and architecture and technology forecasting to design systems more resistant to obsolescence. If designers understand that a subsystem is at high risk of obsolescence, the subsystem may be redesigned or, at a minimum, there should be design changes to enhance the ability to more easily update that subsystem.

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[137] Defense Standardization Program Office, SD-22, "Diminishing Manufacturing Sources and Material Shortages: A Guidebook of Best Practices for Implementing a Robust DMSMS Management Program," January 2016, p. 7.

[138] "U.S. Air Force Fact Sheet," AFRL/RXM–Manufacturing Technology Division, downloaded January 2016.

[139] SME interview, October 2015.

[140] Ibid.

[141] Ibid.

C. Data Capture and Integration Advances

Description of Advances

Advances in data capture and integration are enabled by improved analytical techniques and algorithms for data management, transportability, exploration, and interconnections.

Potential Impact

Using complete technical data to identify replacement items is an important aspect of DMSMS management. However, DOD has a long history of not purchasing data or claiming the intellectual property rights to get the data from OEMs despite acquisition exhortations and regulatory requirements to do otherwise.[142] This problem could be solved with a technology-based solution, but not without disciplined processes to enforce proper use.

Organizations Funding/Working on the Advances

DOD organizations and commercial companies are working to address the problem of disparate data standards and siloed, undiscoverable data.

AFRL is using Spatial Information Management Programming Language both as an easy-to-use programming environment and because it captures and manages a "digital history of data" accessed in multiple programs.[143] AFRL uses DREAM.3D software that has data analysis tools and the ability to ease data transport between collaborators, including 3D data for design.[144] BlueQuartz Software is its DREAM3D implementation expert. BlueQuartz Software tools are cross platform to allow flexibility with different code bases. This integrated software improves the ability to explore data faster and with more flexibility.[145]

AFRL's data capture and integration strategy is leveraging lessons learned from General Electric's aviation business. GE uses Predix, a "powerful new software platform developed by GE specifically to connect people, data and machines over the Industrial Internet."[146] GE has opened up Predix to other software developers, hoping to see this develop into a "big data software platform." GE believes software like this can help integrate and link the physics-based analytical skills of engineers who understand why something is happening with data scientists looking for patterns and connections. "It's this marriage of the physical and digital that creates the most

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[142] SME interviews, November 2015–January 2016.

[143] AFRL, "The Interface of Spatial Information Management Programming Language (SIMPL)," PowerPoint briefing, approved for public release, e-mailed to Institute for Defense Analyses in November 2015 by AFRL.

[144] See http://www.bluequartz.net/.

[145] Ibid.

[146] See http://www.gereports.com/post/99494485070/everything-you-always-wanted-to-know-about-predix/.

powerful result."[147] Predix enables teams in the field to more effectively capture data from devices such as borescopes, wearables, and new robotics.

GE is also using Predix to predict when systems might fail. It is developing Predix applications that run on a smartphone. GE is opening up Predix as a software platform for customers and business partners to write their own software in hopes of becoming the next "Android or iOS of the machine world."[148]

Other aspects of data capture such as "digital thread," ICME, and "Aircraft Digital Twin" are covered elsewhere in this document because there is so much effort being applied to them. Digital thread and Aircraft Digital Twin are discussed in Section 6.5. ICME was discussed in Section 3.2. Associations such as ASTM International are developing and promoting new IT tools to help standardize data and improve data capture and discoverability.[149] The technologies described in this section may help overcome that problem.

DMSMS Application

As DOD's weapon systems age, maintainers are continually challenged to obtain repair parts from a commercial supply base in a constant state of flux. Parts shortages commonly result in exorbitant spare parts costs and may impact readiness. DOD maintainers are often forced to either locally manufacture or locally purchase supply parts in order to fulfill critical customer requirements. However, in many cases, DOD does not possess the design and manufacturing data required to produce the parts or source them commercially.[150]

D. Digital Thread Advances

Description of Advances

The goal of building the "digital thread" is to enable access to accurate data across the enterprise, which would be a great help for DMSMS. While many SMEs interviewed referred to "digital thread," no standard definition of the term, and certainly no succinct, short explanation, was discovered. The basic idea of digital thread is weaving together all data across the firm in any area related to any aspect of the organization's processes.[151] AFRL defines digital thread as "the creation and use of cross-domain, common digital surrogates of a material system to allow dynamic, contemporaneous assessment of the system's current and future capabilities to inform

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147 Ibid.

148 Ibid.

149 John Pace, ASTM International, "ASTM Compass," DMSMS 2015 Conference, December 2015.

150 JTEG meeting, August 25, 2015.

151 LNS Research, "The Global State of Manufacturing Operations Management Software: Weaving the Digital Thread Across Industrial Value Chains," 2014, http://www.lnsresearch.com/research-library/research-articles/the-global-state-of-manufacturing-operations-management-software-weaving-the-digital-thread-across-industrial-value-chains-ebook.

decisions."[152] The goal is to avoid not just duplicative databases, but data silos that only some can access—often with information that may conflict with what exists in another database or document. The goal of Aircraft Digital Twin is to have a complete data version of a new Air Force aircraft, with the full details needed to produce and analyze the physical aircraft.

Potential Impact

The AFRL considers digital thread a "game-changing opportunity" for more rapid development and deployment of new systems. Digital thread also creates a vulnerability by making it easier for enemies to steal systems designs and may make it easier for counterfeiters to steal data.

A 2014 commercial research report noted that large manufacturers pursing digital threads have set targets of 2020–2030 (6 to 16 years out) to achieve full digital thread connectivity.[153] A commercial consulting firm looked at the top challenges of companies pursuing digital thread and found in a survey that 48 percent cited "lack of collaboration across different departments" as the top challenge.[154] DOD has services far more independent and able to ignore or frustrate dictated department standards than commercial companies where chief executive officers and chief information officers can readily dictate standards and force cooperation. The second biggest barrier was "disparate systems and data sources," cited by 39 percent.[155] No commercial organization comes close to the IT database proliferation, duplication, and lack of standards and IT discipline as DOD. In sum, the likelihood of DOD achieving digital thread as fast as a corporation is low.

Organizations Funding/Working on the Advances

As noted earlier, AFRL is pursuing "digital thread/digital twin," a combination of "advanced modeling and simulation tools that link materials-design-processing-manufacturing (Digital Thread)."[156]

Lockheed Martin has been promoting digital thread since 2010.[157] Digital thread is being pursued in many commercial firms, but at this point it is still more of a "concept of a single,

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[152] Ed Kraft, AEDC/CZ, "Expanding the Digital Thread to Impact Total Ownership Cost," NIST MBE Summit, December 18, 2013.

[153] LNS Research, "The Global State of Manufacturing Operations Management Software: Weaving the Digital Thread Across Industrial Value Chains," 2014 (downloaded from lnsresearch.com), http://www.lnsresearch.com/research-library/research-articles/the-global-state-of-manufacturing-operations-management-software-weaving-the-digital-thread-across-industrial-value-chains-ebook.

[154] Ibid.

[155] Ibid.

[156] Pamela A. Kobryn, Air Force Research Lab, "MBE & the Aircraft Digital Thread," NIST MBE Summit, December 17, 2014.

[157] LNS Research, "The Global State of Manufacturing Operations Management Software: Weaving the Digital Thread Across Industrial Value Chains," 2014 (downloaded from lnsresearch.com),

unbroken thread of required information throughout the value chain that is accessible to all departments across the extended value enterprise and ensures complete traceability from design, through production, and to the customer."[158]

Apple has an integrated, digital thread system and the authoritative system to use it and all associated data. With this integrated system, if you change data in one place, it makes simultaneous adjustments everywhere else it needs to. It is one huge, integrated system. Boeing and Toyota also have this.[159] These companies had a single integrated enterprise resource planning system in place that enables this—DOD does not. DOD cannot easily do this with so many independent vendors, service, and agencies. Even within a service, the independence and complexity of different service organizations can thwart standardization.

The Navy is working with NIST and others on data standard development.[160] It is also starting to build a digital thread at depots and has allocated $30 million in capital improvement funding for depots to do this. DOD is pursuing data standardization via the Semantic Web for Interoperable Specs and Standards model evolved from the Boeing concept of "Standards as Digital Data" to smart connected data using linked data models. It is being developed and promoted by the Defense Standardization Program Office and commercial firms.[161]

DMSMS Application

The advantage for DMSMS is achieving complete digital descriptions of systems to facilitate subsequent reengineering or replacement part manufacturing as needed.[162] For DOD and DMSMS, the digital thread would be massive and extremely difficult to achieve. Even if all services and DOD agencies could agree on data formats, software, and processes to achieve a digital thread, it would have to be woven even further for DMSMS purposes—out to commercial suppliers and defense manufacturers.

E. Database, Collaboration Tool, and Information Management Advances

Description of Advances

This section encompasses technologies associated with databases, tools, and information systems used to track parts, company product discontinuation and change notices, and counterfeit

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http://www.lnsresearch.com/research-library/research-articles/the-global-state-of-manufacturing-operations-management-software-weaving-the-digital-thread-across-industrial-value-chains-ebook-.

[158] Ibid.

[159] Liz McNichol, NAVAIR, at Navy DMSMS workshop, November 4, 2015.

[160] Ibid.

[161] Defense Standardization Program Office, "Semantic Web for Interoperable Specifications and Standards," DMSMS 2015 Conference, December 2, 2015; and XSB Inc., "Semantic Web for Interoperable Specs and Standards (SWISS): A semantic view of standards as digital data," Defense Manufacturing Conference, December 2, 2015.

[162] Ibid.

warnings. These technologies also provide supporting functions to search for current and/or replacement parts, find the best prices on replacements, manage cases, manage and analyze bills of material, and predict life cycles and obsolescence. In addition, the ability to work with disparate data standards and multiple databases is provided.

Potential Impact

These technologies enable robust DMSMS management. Steady, continuous improvements in databases and other information management and collaboration tools do not have the excitement of technological advances like AM, but they are essential to the DMSMS management processes.

Organizations Funding/Working on the Advances

These technologies are not new; all organizations involved in DMSMS management use them. Many applications are based on commercial products. Most government and commercial organizations are trying to continuously improve their capabilities in these areas.

DMSMS Application

These technologies enable robust DMSMS management. As these technologies improve, more issues will be identified proactively rather than reactively.

8. Conclusions and Recommendations

On its own, the R&D community identifies and develops a significant number of technological advances useful to the DMSMS community. Most of the 25 technologies cited in this document represent steady advances to older technologies that continue to evolve. Others, like digital thread and multibeam, are more cutting-edge new developments. All of these technological advances will help DOD better address obsolescence and other DMSMS problems, but there are two major barriers to their exploitation by the DMSMS community—knowledge of these current R&D activities and a mechanism to disseminate that knowledge. Insufficient funding of efforts to exploit these technological advances may also detract from exploiting their potential.

Some technology changes may exacerbate DOD's DMSMS problems. Some SMEs indicated that the pace of technology change, commercial application domination, and rapid commercial abandonment of parts in favor of new technologies suggest that DOD will have an increasingly more difficult, costly effort to deal with obsolescence, despite exploiting technological changes that can help mitigate impacts. In addition, many new technological changes may lead to other, sometimes unanticipated changes that can cause difficulties and disruptions. Furthermore, many advanced materials and electronics are only available from overseas commercial sources and this trend may increase as disparities in environmental regulations and legal risks drive more manufacturing and high-tech processes to less-regulated overseas locations.

Additive manufacturing makes it much easier for counterfeit manufacturing of replacement items. Unlike the big plant and equipment requirements of traditional manufacturing, an AM machine is relatively small and cheap. AM could be an opportunity for counterfeiters, allowing small firms and even individuals who can afford it to get the smaller, lower-cost AM equipment—as well as digital design data that may be more accessible via "digital thread"—rather than having to make the investment in reengineering to copy the originals.

The following recommendations should be considered in developing plans to address the opportunities and threats of technological advances.

A. Establish a DMSMS Technology Watch Capability

A key DMSMS technology management issue is, "When should government fundamentally support a new technology/product that may be very useful for DMSMS mitigation but lacks sufficient commercial demand?" There are many existing or potential R&D developments that hold great promise for DMSMS but may not be explored by commercial industry because of its preference for short-life, use-and-dispose products. DMSMS decision makers need to understand likely commercial support and developments to judge whether a promising new technology will get developed and implemented without DOD support. Such support should also consider the need for improved data integration and IT systems that enable these advances. A DMSMS watch capability could be used to identify and make recommendations concerning such situations.

For example, DOD funding and promotion may be worthwhile to achieve DMSMS advantages for advances in interposers, additive repair technologies, qualification, and testing improvements. Multi-beam may be another example of a good case for government support to a company as DOD has such urgent need, but commercial interest may be inadequate because the technology is more suited to low-volume, ad-hoc production.

Some of the technologies with DMSMS potential are well known throughout the community because of their potential contribution to DMSMS management. Others are very military service or center specific and not widely known. With no dedicated effort and responsible party to monitor and pass on information to the DMSMS community, opportunities to exploit or promote promising technological advances may be missed. A DMSMS technology watch capability could also be used to identify and make recommendations concerning such situations. The DMSMS community might even consider making investments to acquire and develop expertise in some of these new technologies.

For example, new, very-low-cost microprocessors developed for hobbyists, such as "Raspberry Pi" ($20), have created a new "ecosystem" of people and software using cheap microprocessors and circuits that let one program a wide variety of applications, including obsolete devices.[163] There may be major applications (though difficult to forecast) for DMSMS from this rapidly evolving network. The DMSMS community needs to sustain an active "technology watch" effort to look for advances that can help DOD deal with obsolescence challenges that are likely to keep getting worse.

B. Expand the DMSMS Conference Role in Communicating R&D Information and Promoting Helpful R&D Advances

The DMSMS Conference has not focused on R&D to any great extent. A significant portion of the conference could be devoted to this subject. Conference tracks could be designed to provide information on the latest developments, the risk areas, and potentially the need for greater investment. As part of this effort, conference planners may want to consider significant outreach beyond defense industries to include more corporate commercial interest to expand the size and scope of technological issues considered. Such outreach should be accomplished by emphasizing obsolescence management and problem mitigation to expose the DMSMS community to more information on promising R&D advances and new industry contacts. These efforts should not be limited to U.S. companies. Interfaces can be built with European and Australian obsolescence conferences where other industries are more heavily represented.

The DMSMS Conference is held in conjunction with the Defense Manufacturing Conference (DMC). The DMC currently does help the DMSMS community stay abreast of new R&D developments of interest. For example, Global Circuit Innovations presented at the December 2015 conference on die extraction/reassembly, which it developed as a faster, low-cost approach to

[163] Michael Nunez, "How the Raspberry Pi Sparked a Maker Revolution," *Popular Science*, June 2015, p. 20.

replace obsolete integrated circuits.[164] R&D tracks at the conference on mechanical, electronic, and management technology advances should be considered to generate more attention, collaboration, and promotion of potentially helpful technology developments. Ideally, DMSMS management would also explore means to disseminate information on R&D advances via establishing communities of interest and other user-focused sharing mechanisms.

C. Do Not Allow R&D Advances to Be Used as an Excuse Not to Apply Best DMSMS Management Practices

R&D advances in techniques for resolving DMSMS issues hold great promise for mitigating the effects of DMSMS issues. These advances, however, are not a substitute for applying the best DMSMS management practices promulgated in the SD-22. This is especially true for additive manufacturing where DOD must be careful not to overly rely on AM for sparing and consequently cut back on spares production and stockpiles. This will lead to more DMSMS issues and more opportunities for counterfeits and malicious insertions. For example, it is important to do the following:

- Design in a way that reduces future DMSMS issues
- Ensure that development and sustainment contracts have effective DMSMS requirements
- Ensure that complete item and system data are owned or readily obtainable
- Conduct life-of-need buys when opportunities present themselves
- Anticipate and proactively prepare for new counterfeiting threats.

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[164] Erick Spory, Doug Schweitzer, Ed Odette, "Die Extraction/Reassembly (DER): A Potential Quick Reaction and Low-Cost Readiness Approach to Solve Integrated Circuit Diminishing Manufacturing Sources Material Shortages," DMSMS 2015 Conference, December 3, 2015.

Appendix A.
Illustrations

Figures

Tables

Appendix B.
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Appendix C.
Abbreviations

AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
AME	Advanced Microcircuit Emulation
ARIC	Assembled Replacement Integrated Circuits
ASIC	Application Specific Integrated Circuits
BOM	Bill of Material
BRASS	Building Resource Adaptive Software Systems
CAD	Computer-Aided Design
CAT	Computerized Axial Tomography
CEO	Chief Executive Officer
CF	Carbon Fibers
CIO	Chief Information Officer
CMC	Ceramic Matrix Composite
CMOS	Complementary Metal–Oxide–Semiconductor
DARPA	Defense Advanced Research Projects Agency
DER	Die Extraction/Reassembly
DLA	Defense Logistics Agency
DMEA	Defense Microelectronics Activity
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DOD	Department of Defense
DOE	Department of Energy
EM	Electromigration
ERP	Enterprise Resource Planning
FPGA	Field Programmable Gate Arrays
FTI	Frontier Technology Inc.
GAO	Government Accountability Office
GEM	Generalized Emulation of Microcircuits
HCI	Hot Carrier Injection
ICBM	Inter-Continental Ballistic Missile
ICE	Integrated Cost Estimating
ICME	Integrated Computational Materials Engineering
IRIS	Integrity and Reliability of Integrated Circuits
ISR	Intelligence, Surveillance, and Reconnaissance
IT	Information Technology
JTEG	Joint Technology Exchange Group

ManTech	Manufacturing Technology
MaSME	Materials and structural, mechanical, and electrical
MOCA	Mitigation of Obsolescence Cost Analysis
NAMII	National Additive Manufacturing Innovation Institute
NAVSEA	Naval Sea Systems Command
NBTI	Negative Bias Temperature Instability
NCDMM	National Center for Defense Manufacturing and Machining
NHA	Next-higher-assembly
NIST	National Institute of Standards and Technology
NUWC	Naval Undersea Warfare Center
OEM	Original Equipment Manufacturer
R&D	Research and Development
R2PI	Rapid Response Process Initiative
SBIR	Small Business Innovative Research
SIMPL	Spatial Information Management Programming Language
SME	Subject Matter Expert
SWISS	Semantic Web for Interoperable Specs and Standards
TDDB	Time Dependent Dielectric Breakdown
TDP	Technical Data Package

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14. ABSTRACT

This document identifies research and development (R&D) advances (including scientific developments, new materials, and manufacturing and management technologies) that might have potential to improve some aspects of DMSMS management. This document does not examine these R&D advances exhaustively or in detail. It provides a brief description of the advances, summarizes their potential impact, highlights some organizations pursuing work in these areas, and points out prospective DMSMS applications. It is designed to be an initial step in increasing awareness and categorizing some of the more important R&D advances that may affect DMSMS management.

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